Fire and Global Soil Carbon

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Introduction

We review the published literature to obtain a broad view of the effect of fire on the global soil carbon pool and estimates of fire effects on the global carbon budget.

Fires tend to transfer carbon from vegetation to detritus and soil, or to volatilize soil carbon into the atmosphere. The amount of carbon transferred can depend on many factors such as fire intensity, soil type and depth, and ecosystem carbon content. The greatest predictor of the soil carbon response is the type and intensity of the fire. Prescribed burns run along the ground, consuming the soil organic layer, whereas wildfire can be manifested in

anything from ground to crown fire. It has been postulated that crown fires volatilize more nutrients than do ground fires because of their intense heat and immense distance from the ground. The most significant responses to fire tend to be concentrated in the first 5 cm of the soil with lesser responses occurring at greater depths.

Fires have many indirect effects on soil carbon amount through impacts on nutrient availability, ecosystem productivity, and species composition effects on types and placement of soil organic matter inputs.

Global carbon cycle models incorporate some aspects of the impact of fires on soil carbon. The main direct effects are usually included but may not be dynamic functions of climate, successional status or other environmental conditions important for simulating fire dynamics under global change conditions.

Grasslands and Chaparral

Grasslands and Chaparral, of all the different ecosystem types, are the most pyrophilic. Subject to periodic fires that maintain species succession and nutrient cycling, easily replaceable grasses and forbs dominate chaparral and grasslands. Fire frequency contributes to low N availability and annually burned prairie is N limited in its primary productivity. According to Johnson and Matchett (2001), "at the individual level, plants compensate for resource imbalances by allocating non-limiting resources to the acquisition of limiting resources." Thus, when low nutrient concentration and the accumulation of carbohydrates are caused by low net N mineralization rates and nutrient limitation, the plant response is to increase energy and C allocation to root growth, leading to a more favorable plant carbon: nutrient balance. The result is roots that have a lower concentration of N in their tissue. It is not known whether the lower root tissue quality resulting from a lack of N causes a change in root tissue quality within a species or whether there is a shift instead to species with a different tissue quality. It is known, however, that C_3 grasses are favored in areas with infrequent fire. The species composition of the chaparral is important maintaining the observed patterns of C and N cycling and feedbacks.

Tiaga

The effects from fire can be seen in Taiga secondary growth forest both immediately and in the long term. Macadam (1987) reported decreases in soil nitrogen and increases in available P nine months after a sub-boreal spruce stand was subjected to broadcast slash burning. Overall, the concentrations of most soil nutrients were found to increase in the forest floor both 9 and 21 months after burning. Results for soil nutrients were more mixed in the mineral soil layer. Forest floor carbon decreased in only a few plots nine moths after burning, while in all the mineral soil plots the levels of carbon decreased. However, 21 months after burning carbon had increased in all layers to amounts that were higher than they had been before the fire. In the long term, Nalder and Wein (1999) found levels of forest floor carbon to be positively correlated to stand age and species.

Tropical forests

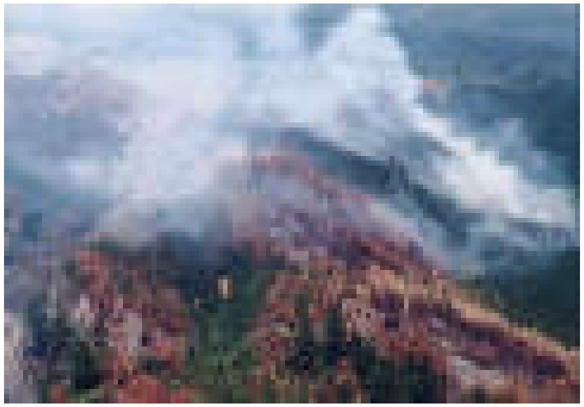
Tropical forests contain a lot of biomass that is lost when deforestation occurs, whether through fire or clear-cutting. However, it has been noted that unless the organic matter layer is consumed the nutrients are conserved for nutrient rich and nutrient poor soils alike. Fire does destroy some of the soil seed bank; Ewel et al. (1981) reports a 52% loss in seeds and 27% loss in species from a Costa Rican tropical forest. Burning stunts re-growth initially, but once pioneer and primary species move in the forests are able to recover, though with the previously mentioned 27% reduction in species.

Temperate forests

In both Pine and Eucalyptus temperate forests rising fire temperatures will increase the amount of labile N released, immediately increasing ammonium levels, with accelerated levels of N mineralization occurring during long-term stand recovery.

In temperate pine forests the death of vegetation and microbial biomass from fire, as well as the consumption of litter and soil organic matter by that same fire, releases labile N which percolates down through the soil, resulting in an increase in soil labile N concentrations (Choromanska and DeLuca)

Six months after the fire, N levels were below pre-burn levels only to recover again after a year. The temperatures reached during burning, with higher temperatures releasing more N, will affect the volatilization of N during a fire. The addition of nitrogen-fixing species increases the biomass and organic matter of the stand, as well as the N content of the mineral soil. Mortality rates may be high with the



addition of species such as Alder because as the stand density increases self-thinning mortality occurs.

Levels of microbial biomass C in plots of burnt Eucalyptus varied according to burn frequency. Plots that had only burned once had higher soil biomass C than unburnt plots that in turn had higher C concentrations than frequently burned plots. One explanation for this trend is that while fire may make nutrients readily available to organisms, repeated fires will make nutrients scarce as more are volatilized.

Wetlands

In wetland ecosystems fire has the potential to alter the composition of the vegetative community. Fires will consume only a portion of aboveground vegetation, while moisture-laden roots and soils layers remain unharmed (i.e., surface fire) (Smith et al., 2001). Frequent fires will alter the make-up of successional species by selecting for those that most readily adapt to post-fire conditions. During dry conditions peat fire can occur, combusting the soil organic matter and wiping out vegetation and portions of the seed bank. The combustion of the soil organic matter leads to lower ground elevation and as a result, increased water depth. Higher water depth alters the hydroperiod of the wetland, again creating a situation where certain species, this time flood-tolerant ones, are at an advantage during plant community succession. However, the effects of fire on the concentrations of soil nutrients will have the greatest effect in determining which species return.

Permafrost

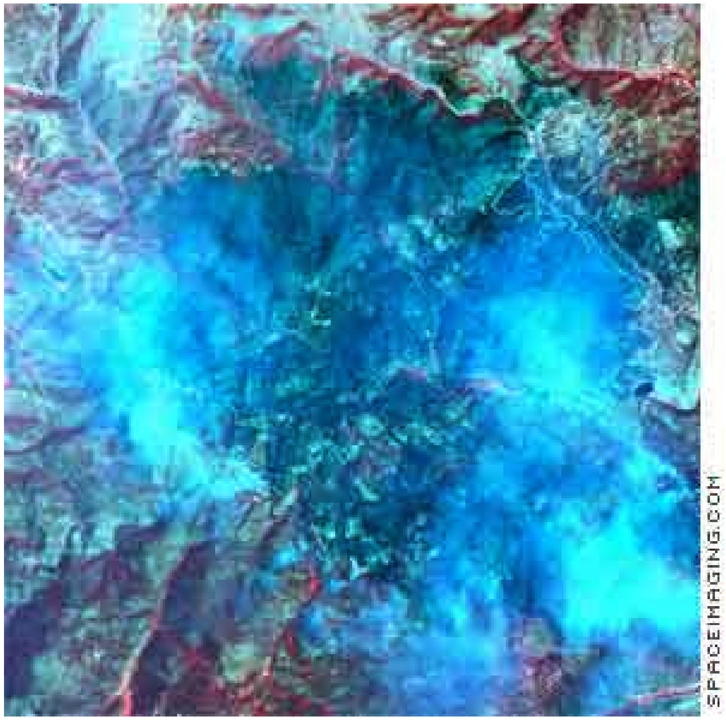
The heavy organic matter layer (composed of mosses, lichens, and litter) of permafrost soils maintains their frozen state. Its makeup is such that heat from the soil is readily conducted up in winter, but solar radiation is not so well conducted downwards in the summer. Fire decreases the depth of the soil organic layer, allowing a greater defrostation (nearly three times as much) of permafrost soils in summer. However, in burnt areas the increased thaw depth is transitory. It takes approximately 30-50 years for the moss and litter layers to recover, after which the soil thaw depth again decreases. Wildfires that occur on steep slopes can cause an unusual form of soil heating known as thermokarst-soilflux. The organic layer is destroyed by fire leaving the slope exposed to the effects of erosion. Heavy rains and natural springs wash away the newly exposed soil, causing the permafrost soils to actively thaw, intensifying the erosion process already occurring and preventing the restoration of moss and litter. Active thawing may result in the generation of icy lenses and mud streams which throw out large masses of mud as they rush down the slope.

Terrestrial biogeochemistry models

Global terrestrial biogeochemistry models depicting the exchange of carbon between the atmosphere and the land surface provide some method of representing effects of disturbances including fire on the carbon cycle. Fire frequency and extent in terrestrial ecosystems depends on many factors that are related to climate directly (fuel moisture content, relative humidity, temperature, convective storms for lightning ignition) and indirectly (amount and type of fuel resulting from ecosystem productivity and species composition, suitability for human exploitation). Only those models that explicitly consider fire are capable of estimating the net exchange of carbon with the atmosphere in the future under altered climate conditions and human management.

In the models that have an explicit treatment of fire, there are generally only limited ranges of processes that impact soil carbon. In general, these models do not incorporate a direct loss of carbon from mineral soil layers. In some models it is difficult to distinguish surface organic accumulations from soil carbon such as in the highly lumped compartments of TEM (McGuire et al. 1999). As a result, the difference between control burns and wildfire noted by Johnson and Curtis (2000) cannot be simulated by these models. Some models do calculate fire intensity. The intensity determines the amount of biomass consumed or killed and the amount of litter consumed but does not determine the degree of combustion or transformation of organic carbon in mineral soil. Changes in soil hydrophobicity and leaching of soluble components after fire are also not considered.

All models do incorporate some aspect of changes in levels of organic matter inputs into soil as the result of fires. In some of these models, the fraction of fine and coarse litter consumed is based on ecosystem averages. Changes in fire intensity based on fuel load and environmental conditions, however, may change regionally and under future climate. In other models, the reduction of organic matter inputs into soil is a function of fire intensity and conditions that influence fire intensity such as amount and moisture content of fuel or weather conditions. Similarly, the amount of biomass pools killed, which represents additional organic matter inputs into the litter and soil layers, may be ecosystem averages or a function of fire intensity. In those models that explicitly treat the nitrogen cycle coupled to the carbon cycle, losses of N through volatization, and mineralization of N by fire are normally estimated using average values based on C/N ratios.



There are many ecosystem effects of fire on soil carbon that are not explicitly treated by global carbon cycle models. These include fire-induced changes in species composition, especially the establishment of legumes after fire, short-term erosion, changes in hydrology due to the formation of hydrophobic substances, and changes in the belowground nitrogen dynamics. Global models do not treat explicit changes in microbial populations and function. Many of the processes are currently omitted because they are special cases that vary in importance among ecosystem types and landscape position. However, in some cases the effects of the some of these processes, like legume establishment after fire in western US conifer forest, man occur over sufficiently large areas that explicit evaluation of them may be warranted.

Models

Model	HRBM (Mack et al. 199?)	TEM (Starfield and Chapin 1996)	MC1 (Lenihan et al. 1998)	CENTURY (Parton et al. 199?)	IBIS	Biome-BGC (White et al. 2000)	LPJ (Thonicke et al. 2001)
Fire Frequency	Constant	Constant	Computed	Scheduled		Constant	Constant
Fire Intensity		w/ ALFRESCO	Yes				Yes
Soil C Consumed							
Inputs Consumed	Yes	Yes	Yes	Yes		Yes	Yes
Killed Biomass	Yes	Yes	Yes	Yes		Yes	Yes
Organic C Transformation	Charcoal						
Organic N volatilized		Yes	Yes	Yes (also P, S)		Yes	Yes
Organic N Mineralized		Yes	Yes	Yes		Yes	Yes
Species Composition		w/ ALFRESCO	Yes	Indirect (C/N ratio)			Yes
Short-term Erosion				No		Yes	
Hydrological changes			Indirect	Indirect		Indirect	Indirect
Microbial changes							

Thank You

Special thanks to:

- Global Change Education Program
- Mac Post, my DOE mentor